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Construction and Testing of an Inexpensive PAR Sensor

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Construction and Testing of an Inexpensive PAR Sensor

Peter Fielder and Phil Comeau

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ABSTRACT

Detailed studies of light in forest canopies typically require a large number of light sensors. However, the high cost of commercially available sensors can make such studies very expensive. This report describes the construction and testing of a practical, rugged, and inexpensive sensor for measuring photosynthetic photon flux density. Detailed instructions are provided for assembly and calibration. The sensor was made from a gallium arsenide phosphide (GaAsP) photodiode held within a protective casing of acrylic and aluminum. The LI-190 Quantum Sensor (LI-COR Inc.) was used as a standard for comparison. The stability of the GaAsP sensor compared favourably with the LI-190 during a 24-month open-sky test. Results from nine GaAsP sensors exhibited signal drift of 3–23%, and from four LI-190 quantum sensors of 5–18.5%. The GaAsP sensors generally drifted by <6% over a single season except for one of the Type 1 sensors (#42) that displayed intermittent signal drift. Open-sky daily calibration coefficients of GaAsP Types 2, 3, and 4 showed that about 95% of the data points were within 2–4% of the mean for June to September 1998, and within 3–10% of the mean for January to November 1999. Data variability almost doubled during the wetter months and Type 1 (#41 and #42) sensors were particularly affected. GaAsP (Types 2 and 3) and LI-190 sensors exhibited similar signal drift beneath a canopy as in the open-sky test. Daily calibrations made beneath the canopy were variable over the season, suggesting that care should be taken in making *in situ* calibrations. Field testing beneath a birch canopy indicated that, compared to a quantum sensor (LI-190), one GaAsP sensor had a spectral response error of <7% in the densest canopy. Recommended sensor care includes minimizing contact with humidity, frequent calibration (pre- and post-season), frequent field checks, and regular maintenance, including diffuser cleaning. Low cost may make these sensors desirable for studies that require a large number of sensors.

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We wish to thank the reviewers Ralph Adams, Dave Spittlehouse, and Tony Letchford for their valuable criticisms. Also we acknowledge Tony Letchford for the instructions on how to build the support posts for the sensors. Funding for this work was provided by Forest Renewal BC in conjunction with research project HQ96400-RC.

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INTRODUCTION

The light regime within the forest has a substantial influence on growth and survival of tree seedlings. The need to develop predictive models of forest growth in complex stands has led to a continuing interest in the light environment. Information on understorey light conditions and how they relate to survival and growth of understorey trees is of particular interest in many partial cutting and mixedwood management studies. One approach to characterizing and quantifying light distribution below the canopy is to deploy a number of fixed sensors and continuously record light levels throughout the growing season. However, the number of sensors required can be prohibitive for many research budgets, so there is much to be gained from building an inexpensive custom sensor as an alternative to the many proprietary sensors available.

In forest stands, the most common types of sensors used to measure radiation are thermoelectric and photoelectric. Thermoelectric sensors measure temperature differences using a thermocouple or thermistor as a transducer to convert radiant energy to electrical energy. They are used mainly for solar and longwave radiation measurements and have the property of equal response over their wavelength range. The photoelectric type, here referred to as photodiodes (see Glossary), are solid-state devices that convert light energy (photons) to electrical current (Pearcy 1989; Hamamatsu Corp. 1995). Photoelectric sensors are particularly useful for measuring the light required by plants for photosynthesis, because they respond to the photon flux over the photosynthetically active wavelengths.

The accepted wavelength band for photosynthetically active radiation (PAR) (see Glossary) measurement is 400–700 nm, and is commonly referred to as the visible light spectrum. Several types of photodiode ar suitable for light measurement in the visible range. These include silicon (Si), selenium, cadmium sulfide, lead sulphide, lead selenide, and gallium arsenide phosphide (GaAsP) photodiodes (Unwin 1980; Pearcy 1989). Of these, Si and GaAsP photodiodes are the most useful (Pearcy 1989). An Si photodiode (blue enhanced) is used in the LI-COR quantum sensor (LI-190 SA or SB), which is one of the most widely used for monitoring photosynthetic photon flux density (PPFD) in ecophysiological studies. The LI-190 has benefited from years of product development, but owes many of its design features to the efforts of researchers in the 1960s. Workers such as Federer and Tanner (1966) and Biggs et al. (1971) developed, and improved upon, the filter arrays and sensor-head design that achieved near-ideal photon response (see Glossary) and a high degree of cosine correction. These features allowed for the measurement of PAR beneath canopies without fear of a significant offset due to a change in the quality of incident light.

With respect to building an inexpensive alternative to a proprietary sensor for measuring PAR, Gutschick et al. (1985), Pontailler (1990), and Aaslyng et al. (1999) have shown that GaAsP photodiodes have some advantages over Si and other types of photodiodes. These advantages include several cost-saving features: (1) relatively low per-unit cost, (2) spectral response close to the 400–700 nm band (for the planar diffusion type) (no expensive filter array necessary), and (3) insensitivity to ambient temperature (no need for temperature compensation). Other desirable qualities include a relative insensitivity to lead resistance, a very linear response to quantum flux (no need for complex polynomial fitting), a rapid rise time, and a near-

Lambertian angular response, allowing easily achieved cosine correction (Gutschick et al. 1985; Pontailler 1990). Several studies have demonstrated the practical application of GaAsP photodiodes as a substitute for commercial sensors when a relatively large number of sensors is required. Such studies include the effects of light quality and quantity on plant growth and photosynthesis (Tinoco-Ojanguren and Pearcy 1995), and for comparing methods of estimating PPFD under canopies and in gaps (Chazdon and Fletcher 1984; Easter and Spies 1994; Gendron et al. 1998).

This report describes the procedure for constructing a robust GaAsP sensor for field use and presents results from calibration and test runs of variations on the basic design, illustrating the important features and errors that might be expected.

BUILDING A FIELD PAR SENSOR

General Sensor Specifications

In addition to low cost, the following specifications were considered in the construction of a field PAR sensor. The sensor should:

- be rapid and stable, and preferably have a linear response over a wide range of light levels
- have a low temperature coefficient
- have a known spectral response, preferably in the range of 400–700 nm
- be cosine-corrected
- be resistant to moisture and rough handling
- have a sensor head that drains during wet weather
- be easily levelled in the field
- lend itself to a convenient and repeatable calibration methodology
- be fabricated with a minimum of specialized equipment

The LI-COR LI-190 Quantum Sensor —The Standard

The LI-COR LI-190 quantum sensor (LI-COR Inc., Lincoln, Nebr.,) was used in this study as the standard of comparison for the GaAsP sensors during testing and calibration. The LI-190 sensor measures photosynthetically active radiation (PAR) (400–700 nm) and is calibrated in $\mu mol \cdot m^{-2} \cdot s^{-1}$ (LI-COR 1986). The spectral response of an LI-190 and the ideal photon response are shown in Figure 1. The sensor response is designed to approximate the photosynthetic response of plants. To achieve this, the sensor contains a silicon diode, enhanced in the visible wavelengths. However, because the Si photodiode has a spectral response range from ultraviolet to infrared, the 400–700 nm waveband is selected by combining visible bandpass interference filters and coloured glass filters mounted in a cosine-corrected head.

The instruction manual for the LI-190 suggests that typical applications are for light measurements within plant canopies, greenhouses, growth chambers, laboratories, and remote environmental monitoring sites, and states that relative errors under the different light sources are within 5% (LI-COR 1986). The sensor has excellent linearity (1% up to 10 000 $\mu mol \cdot m^{-2} \cdot s^{-1}$), stability (<2% over a 1-year period), a low temperature dependence (0.15% per °C), and cosine correction up to 80 degrees from the zenith. In our experience, these sensors generally have the qualities claimed, as long as they do not come into prolonged contact with moisture, which may cause them to malfunction (see Sensor Testing).

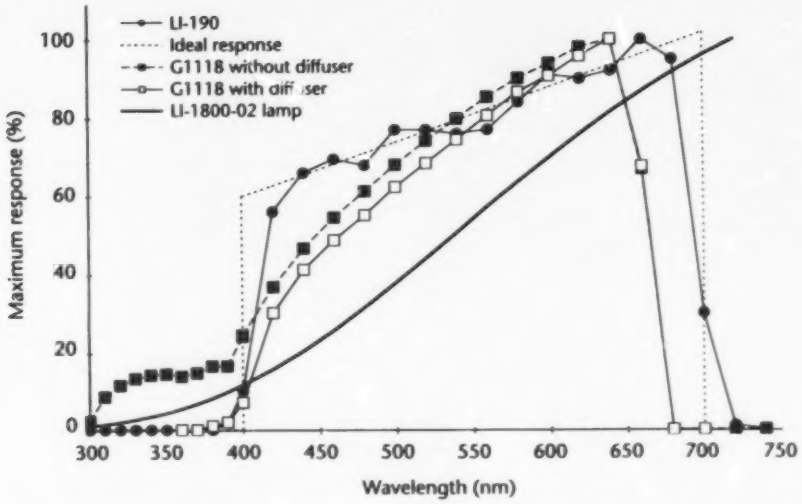

FIGURE 1 *Spectral responses of the LI-190 quantum sensor, the ideal quantum response, and the GaAsP planar diffusive type photodiode (G1118) with and without the influence of the diffuser material. The spectral output of the quartz tungsten halogen lamp of the LI-1800-02 Optical Radiation Calibrator is also shown for comparison. Sources of data shown: LI-190 quantum sensor and ideal quantum response (LI-COR 1986), halogen lamp calibration data (LI-COR, Lincoln, Nebr.), G1118 photodiode (Hamamatsu Corp. 1995), Acrylite GP 015-2 diffuser material (Cyro Canada Inc., Mississauga, Ont.).*

Photodiode Selection

Photodiode selection was initially based on the experience of previous researchers with GaAsP photodiodes (Gutschick et al. 1985; Pearcy 1989; Pontailler 1990). The GaAsP photodiode (planar diffusion type) has the desirable qualities of rapid rise-time, relatively low temperature coefficient, and spectral response close to the 400–700 nm waveband (Figure 1). Other GaAsP photodiode types can be used, but they have a slower rise time and broader spectral response in the UV range (Aaslyng et al. 1999). However, wavelengths below 400 nm can be blocked with a diffuser of acrylic or polycarbonate. The GaAsP planar diffusion type is available in a number of different "packages" as described in the Hamamatsu catalogue (Hamamatsu Corp. 1995). Some of the available photodiodes are shown in Table 1.

Photodiodes G1115, G1118, G3067, and G2711-01 were tested initially to see which were the most suited to our purposes. The samples were mounted directly on top of nylon round stock, with or without a light-diffusing cap of nylon (polyamide) or Teflon™ but with no other attempt at cosine correction. The sensors were mounted on a calibration plate and placed in the open for at least 24 hours. They were wired to a Campbell Scientific Inc. CR10 datalogger with a 100-ohm resistor to convert the current to a measurable voltage. Regression analysis showed that photodiodes with the "TO" packages had the poorest agreement with the LI-190 quantum sensor. Regressions (r^2) for the G3067 and G1115 were 0.965 and 0.966, respectively. These photodiodes were discarded in favour of the remaining package types, the ceramic G1118 ($r^2 = 0.986$) and the plastic G2711-01 ($r^2 = 0.981$) for further testing. The G1118 tended to slightly underestimate, but a small improvement in r^2, from

TABLE 1 *Features of GaAsP photodiodes (planar diffusion types) available from Hamamatsu Corp. (data from the company catalog). Photodiodes, indicated in the table with bold types were purchased for testing.*

Wavelenth (nm)	Peak sensitivity (nm)	Photodiode	Package	Window material	Active area (mm)	Rise time (μs)
300–660	640	**G1118** [a,d]	Ceramic	Resin coat	1.3 × 1.3	1
		G1115 [a,d]	TO-18[c]	Borosilicate glass	1.3 × 1.3	1
		G1116 [a]	TO-5[c]	Borosilicate glass	2.7 × 2.7	4
		G1117 [a]	TO-8[c]	Borosilicate glass	5.6 × 5.6	15
		G2711-01 [b]	Plastic mold	Resin coat	1.3 × 1.3	1
		G3067 [a]	TO-18[c]	Lens-type Borosilicate glass	1.3 × 1.3	1
400–760	710	G1738 [a,e]	Ceramic	Resin coat	1.3 × 1.3	0.5

a Operating range -10 to +60 °C
b Operating range -10 to +70 °C
c "TO" packages have the light-sensitive area enclosed within a metal canister with a borosilicate glass window
d Similar to GaAsP photodiode used by Gutschick (1985) and Tinoco-Ojanguren and Pearcy (1995)
e Photodiode used by Easter and Spies (1994)

0.986 to 0.991, was gained by adding a neutral diffuser without modifications to the sensor head. For the G2711-01, the r^2 relationship was improved from 0.981 to 0.992 with the addition of a neutral diffuser.

These early designs were difficult to level properly, and non-symmetrical diurnal light curves were common. Improvements on the design resulted in fully functional units using the two preferred photodiodes (G2711-01 and G1118). These two photodiodes are shown in Figure 2. The G2711-01 was chosen initially because it was less expensive and had better angular response than the G1118. However, the G1118 was used in later models because the G2711-01 was not available. The performance of these photodiodes is described under Sensor Testing.

FIGURE 2 *GaAsP sensors in various stages of assembly. From right to left in the foreground: the translucent acrylic diffuser, the G2711-01 and G1118 photodiodes with 30-gauge leads. From right to left in the background: the clear acrylic sensor housing with machined port for the photodiode, an aluminum sleeve, a complete sensor showing lead port, and the complete sensor with lead, plug, and label.*

Signal Measurement of the GaAsP Sensor

Photodiodes are current-generating devices and current may be measured directly with a high-quality meter that can measure in the nanoamp (10^{-9}) range. To store data, a datalogger, such as the LI-1000 (LI-COR, Lincoln, Nebr.), is required. Other dataloggers, such as the Campbell Scientific CR10, are voltage measuring devices in which the signal can be converted to voltage if a resistance is put across the photodiode terminals (see Appendix 2 for program). Pearcy (1989) suggests keeping the resultant voltage below 10 millivolts (mV) at maximum light levels to maintain linearity. However, we have used up to 20 mV (sunny day in June) with a resistance of 618 ohms without detectable loss of linearity. Hamamatsu Corp. suggests that linearity would probably be acceptable up to 100 mV (E. Hergert, Hamamatsu Corp., pers. comm., Feb. 1999). It is noteworthy that the resistance needed to generate 10 mV will vary according to the type of diffuser used in the finished sensor.

If the leads are connected to perform single-ended (SE) measurements, up to 12 sensors can be connected to the CR10 datalogger. For an SE measurement, one terminal should be connected to an SE input and the other to analog ground (AG). The leads may be switched if a negative reading results. The mV value can be recorded and converted to PPFD later. However, for ease of spot checking the sensor output in the field, it may be desirable to include the calibration coefficient in the program so that it reads in $\mu mol \cdot m^{-2} \cdot s^{-1}$ (see Calibration). A detailed treatment of datalogger installation, operation, and maintenance may be found in Spittlehouse (1989).

Sensor Housing for the GaAsP Photodiode

General comments The sensor housing consists of the sensor head and body. The sensor head allows light to be received by the photodiode from all directions above horizontal. A translucent acrylic diffuser protects the photodiode and provides for cosine correction. General design proportions for the sensor head and choice of material for the diffuser were taken from Kerr et al. (1967) and Biggs et al. (1971). The sensor body supports the photodiode so that it can be easily levelled and positioned on a support.

Enclosing the photodiode in a robust watertight container with a translucent window (diffuser) gives good protection from most environmental assaults (i.e., humidity, UV radiation, and mechanical shock). Moisture probably causes the most problems beneath forest canopies in British Columbia, where the mean annual precipitation can vary from 600 to 4000 mm annually. A drain hole in the sensor head prevents water from pooling on top of the sensor. This minimizes significant departures from the calibration value in wet weather and also slows the gradual diffusion of moisture through the acrylic diffuser. Water droplets may still sit on the diffuser, but errors appear to be small compared with those caused when a water lens forms over the whole sensor head.

Materials and construction Components of the GaAsP sensor are shown in Figure 2 and in cross-section in Figure 3 (see Appendix 1 for detailed assembly procedures).

We preferred to have all cutting, drilling, and machining done in a machine shop to achieve finer tolerances, but this cost could be avoided if a lathe and well-equipped workshop is available. Metric dimensions have been given but Imperial measures are still in common usage .

We used acrylic for the sensor body and diffuser because it is resistant to yellowing, can be machined, and can be bonded with methylene chloride.

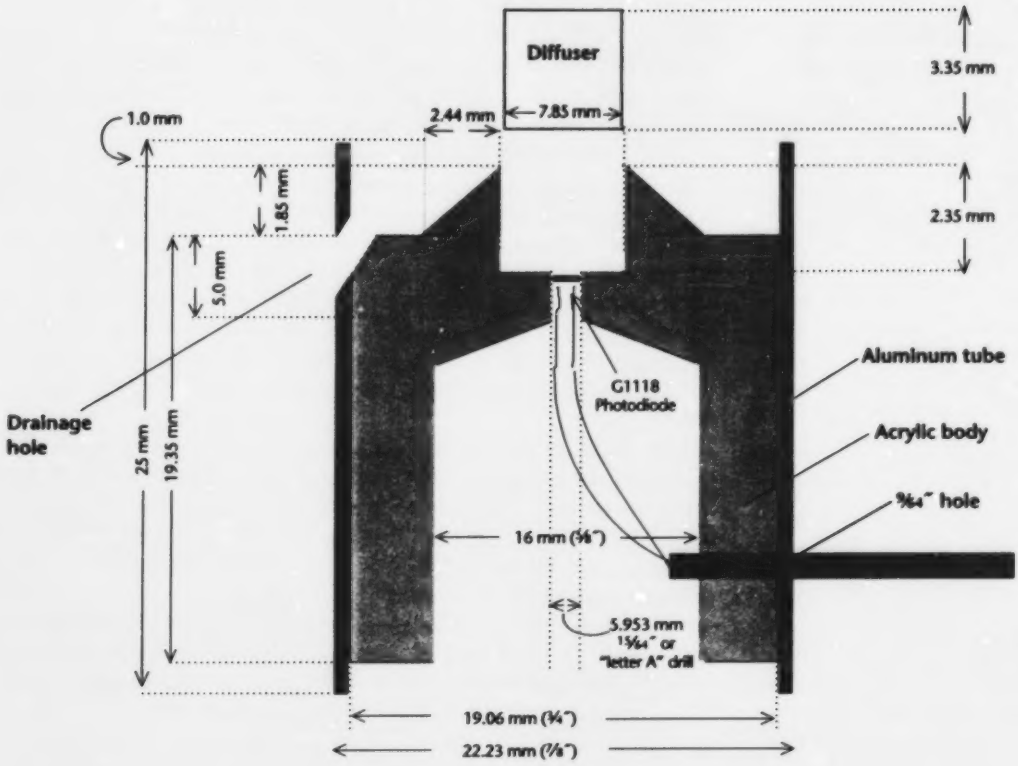

FIGURE 3 *Cross-section of GaAsP sensor showing assembly and dimensions.*

Cast 19.06 mm (¾") diameter clear acrylic round stock was used for the body and 3.34 mm (⅛") thick cast translucent ("sign-white") acrylic sheet (Acrylite GP 015-2, Cyro Canada, Inc., Mississauga, Ont.) for the diffuser. The diffusers were cut from sheet material by laser. Diffuser and sensor body were bonded together using methylene chloride to reduce the possibility of delamination and subsequent moisture penetration into the photodiode. The aluminum outer sheath (outer diameter 22.23 mm [⅞"], internal diameter 19.06 mm [¾"]) provided rugged protection and a level base, and created the rim necessary for the cosine-correcting head without extra machining of the acrylic. The aluminum sheath also prevented light from penetrating the side of the clear acrylic sensor body, eliminating the need to paint to maintain opacity (opaque cast acrylic round stock is very hard to find). Aluminum sheath and acrylic body were cemented together using a slow-curing epoxy resin. Several applications of matte-black enamel model paint (Testors) were used to prevent light penetration through the top surface of the acrylic body. An exterior-grade matte-black vinyl was also used to exclude light, with good results. The G1118 and G2711-01 were the two GaAsP photodiodes used in subsequent variations on the basic design.

Each sensor was provided with a 40–50 cm lead of unshielded, 22-gauge, single-pair, multi-stranded communications wire (Belden #9502-U) terminating in a 16-gauge trailer plug. This arrangement provided quick connection and disconnection for calibration and repair in the field. The diameter of the lead port was such that the lead end, with a covering of

⅛″ shrink wrap, would push through with some twisting. The lead was held in place on the inside by a small cable tie and sealed with non-corrosive sealant. Extension leads in the field should be shielded to eliminate noise due to electrical fields and radio signals. All connections should be soldered, taking care not to damage the photodiode. Finally, each sensor should be labelled with a permanent unique number to identify it and track successive calibrations.

Sources of Error of the GaAsP Sensor

Since the response of the GaAsP photodiodes is linear over the range of daylight irradiance (Hamamatsu Corp. 1995), the chief sources of deviation from the calibration standard are spatial error (i.e., cosine and azimuth error), temperature dependence error, spectral response error, and signal drift error.

Spatial error Spatial errors can be minimized by ensuring that both diffuser and photodiode are level with the outer rim of the sensor (the sensor is carefully levelled) and that the head is cosine corrected.

Temperature dependence error Temperature coefficient is low, about +0.08% per °C near 20°C (Pontailler 1990), and our testing suggests an error of about 3% over 15°C between 20 and 35°C.

Spectral response error The spectral response error is not known, but can be minimized by calibrating the sensors under natural daylight. Because the GaAsP photodiode is not a perfect quantum sensor (Figure 1), errors will occur beneath the canopy if the sensors are calibrated against the LI-190 quantum sensors under an open sky. Pearcy (1989) calculated this offset to be 3.2% higher than the quantum sensor under a tropical canopy. Pearcy (1989) was of the opinion that this error was tolerable when set against the benefits of being able to use a large number of low-cost sensors.

Signal drift error Long-term drift in calibration may occur through changes in photodiode response over time. Data on long-term stability of GaAsP photodiodes were not provided by the manufacturers. Long-term changes may also result from changes in the quantity, or spectral quality, of the transmitted light through the diffuser due to weathering. The magnitude of the weathering effect is unknown but may be significant for sensors continuously exposed to solar radiation. Failure to clean diffusers can cause significant errors, especially beneath dense canopies where insect exudates, dust, and debris are constantly raining down on the sensors. A typical error beneath a canopy after several months could be 3–7% but might be as high as 18% in very dirty environments. Even those sensors in the open showed a change of 1–3% over a month, which was reversed by cleaning.

Cosine Correction of the GaAsP Sensor

The sensor included a cosine-correcting head to minimize spatial errors due to cosine and azimuth errors. Cosine correction is important if measurements are to be made throughout the day and throughout the year, particularly under open sky.

The sensor head is similar to the one used by Biggs et al. (1971). Cosine correction was achieved by blocking any light striking the sensor from below the horizontal (aluminum rim), scattering and attenuating the light arriving at the photodiode by using a diffuser, and compensating for reflection off the diffuser surface at low sun angles by exposing part of the diffuser edge. The

two critical measurements for cosine correction are the height of the exposed edge of the diffuser and the distance from the edge of the diffuser to the inside of the rim provided by the aluminum outer sheath. According to Biggs et al. (1971), the diffuser height should be one-seventh of the distance between the diffuser edge and the inside of the outside rim. For our sensor this would be a height of 0.8 mm.

We custom built a simple apparatus to test the conformity of GaAsP sensor response to Lambert's cosine law (see Appendix 1 for details). One set of measurements from 0 to 86 degrees from the zenith in one plane was made for each sensor. Deviation of the test sensor from the true response was calculated using the following formula (from Kerr et al. 1967):

$$\text{True response (\%)} = \left(\frac{R(\theta)}{R(0)}\cos\theta\right)100,$$

where θ = the angle from the zenith,
$R(\theta)$ = the sensor response at angle θ, and
$R(0)$ = the sensor response when $\theta = 0$.

Figure 4 shows how changing the height of the diffuser edge can affect the cosine correction compared with that of a bare photodiode (G1118). The GaAsP sensors were a considerable improvement over the bare photodiode at angles larger than 50 degrees. These sensors were within 5% of the true response for angles from the zenith of 50, 65, 75, and 80 degrees, for diffuser heights of 0.7, 0.8, 0.9, and 1.0 mm, respectively. Empirical evidence from the test sensors shows that a height of 1.0 mm (rather than the theoretical 0.8 mm) would have resulted in a better cosine response, in that it mimics that of the LI-190. Using the same equipment, the LI-190 was within 5% of the true response for angles up to 80 degrees. These test findings have been incorporated into the recommended design.

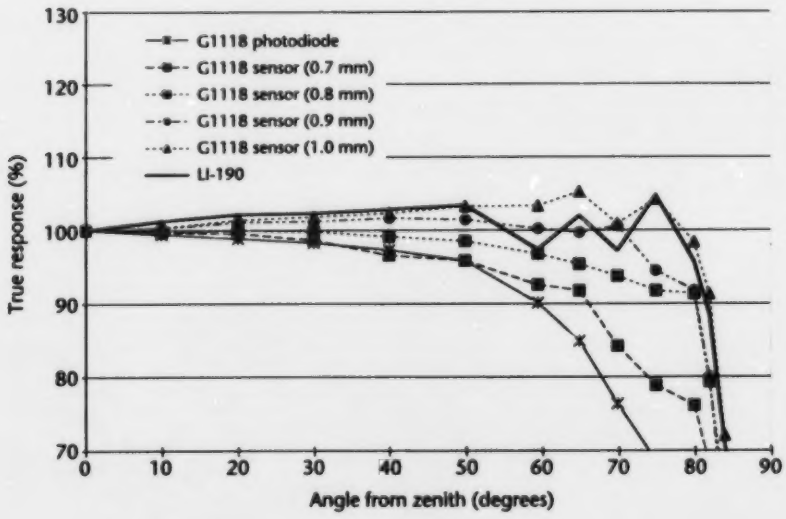

FIGURE 4 *Response curves for the G1118 sensor with different diffuser heights. Shown are curves for a bare G1118 photodiode with no cosine correction, and sensors with the diffuser recessed to four depths, resulting in diffuser heights of 0.7, 0.8, 0.9, and 1 mm. The response of an LI-190 was measured using the same apparatus.*

Calibration

Calibration is the process of deriving a coefficient to convert the raw signal from the GaAsP sensor to readily quantifiable units; in this case, photosynthetic photon flux density (PPFD) in $\mu mol \cdot m^{-2} \cdot s^{-1}$. The standard for this conversion can be a previously calibrated quantum sensor (LI-190) or a standard lamp with an output traceable to a primary standard lamp at the National Institute of Standards and Technology (NIST), Gaithersburg, Md.

Calibration under solar radiation To calibrate a GaAsP sensor for solar radiation, we mounted it on a calibration plate (Figure 5) beside at least two calibration standards (LI-190), and collected data under open skies for a full day, typically 04:00–22:00 h. The array was made up of two square 6.35 mm (¼″) aluminum plates (15 × 15 cm). The top plate was drilled with three 23.60 mm (60⁄64″) holes to accommodate the LI-190 sensors and eight 22.23 mm (⅞″) holes with equidistant centres (34 mm) to accept the test sensors. The two plates were screwed together so that the bottom plate provided a flat base for each sensor. A 15.875 mm (⅝″) hole was drilled in the lower plate beneath each sensor to allow water to drain and to make sensor installation and removal easier. Three threaded holes were drilled in the form of an equilateral triangle and bolts were threaded through the holes (Figure 2). The bolts were used to level the array and each sensor was checked individually using a bubble level. A small bubble level distributed by LI-COR was found to be ideal for this purpose, as it was the correct diameter to rest on the rim of the LI-190 and GaAsP sensor.

Data were collected and stored as 10-minute averages of 1-second scans (see Signal Measurement and Appendix 2). Data were analyzed using the re-

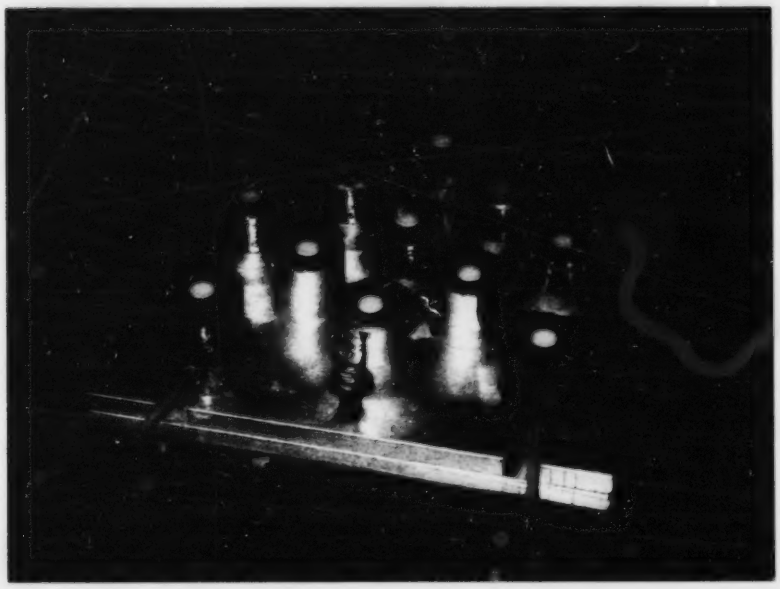

FIGURE 5 *Calibration plate used for open-sky calibrations of GaAsP sensors using the LI-190 quantum sensor. Shown are eight silver-coloured GaAsP sensors arranged inside a triangle of three LI-190 sensors (black), two in the foreground and one in the centre in the background.*

gression procedure in the SAS statistical package, version 6.12 (SAS 1990). The procedure was run separately for each day, with the test sensor millivolt value as the independent variable and the average of the calibration (LI-190) sensors as the dependent variable. As a rule, the intercept was very small and the r^2 very high; therefore, to simplify signal adjustment of each sensor, the intercept was forced to zero. The slope parameter from the regression was used to convert the mV signal to PPFD, effectively calibrating the sensor.

Standard lamp calibrations The LI-1800-02 Optical Radiation Calibrator uses a 200-W quartz tungsten halogen lamp (standard lamp) calibrated via transfer calibration (traceable to the NIST) to a 1000-W working standard lamp at LI-COR's laboratories. The absolute calibration accuracy of the LI-1800-02 standard lamp is ±4% from 350 to 1000 nm. The lamp output was approximately 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, depending on the individual calibration. The radiation output spectrum of the lamp compared to the spectral response of the LI-190 and the GaAsP photodiode with and without diffuser is shown in Figure 1.

Both LI-190 and GaAsP sensors were calibrated using the LI-1800-02 standard lamp. For the GaAsP sensors it was necessary to build an adapter to hold the slightly smaller-diameter GaAsP sensors in the same position as the LI-190 in the calibration port. Unfortunately, we found that GaAsP sensors could not be calibrated directly for solar radiation with the LI-1800-02 (see Sensor Testing). However, the standard lamp calibration was used to track GaAsP calibration drift. A previous GaAsP calibration value for solar radiation could then be adjusted proportionally, according to the change in the standard lamp calibration over the season. The LI-190 sensors were calibrated directly with the standard lamp. Sensor response was measured in microamps (μA) to derive a calibration constant (Ca) in $\mu A/1000\ \mu mol \cdot m^{-2} \cdot s^{-1}$. Because we used the Campbell Scientific CR10 datalogger, it was necessary to derive a calibration constant for voltage measurement (Cv) depending on the resistance used. The calibration constants may be derived as follows (LI-COR 1986):

For measurement in μA:

$$\text{Calibration constant (Ca) in } \mu A/1000\ \mu mol \cdot m^{-2} \cdot s^{-1} = \frac{\mu A \times 1000}{\text{standard lamp output } (\mu mol \cdot m^{-2} \cdot s^{-1})}$$

For measurement in mV:

$$\text{Calibration constant (Cv) in } mV/1000\ \mu mol \cdot m^{-2} \cdot s^{-1} = \frac{Ca \times \text{resistance (ohms)}}{1000}$$

$$\text{Calibration Coefficient} = \frac{1000}{Ca \text{ (or Cv)}}$$

The purpose of sensor testing was to evaluate the performance of the GaAsP sensor compared with the standard LI-190. Acceptable performance has both short-term and long-term components. In the short term, comparing diurnal curves from both sensors can indicate how faithfully the GaAsP sensor tracks the LI-190. The more linear the relationship, the greater the reliability of instantaneous measurements collected throughout the day. Large errors would most likely be a result of poor cosine correction. Long-term variability would indicate stability problems. This problem was addressed by obtaining readings from GaAsP and LI-190 sensors placed side-by-side under an open sky for 24 months. Also, approximately once a month all the sensors were tested using the LI-1800-02 standard lamp. This approach also served as a check of the stability of the LI-190 standard over time. Finally, field data from pairs of GaAsP and LI-190 sensors were used to examine sensor performance beneath the forest canopy.

Linearity of the GaAsP Sensor versus the Quantum Sensor

Figure 6 shows the relationship between the output of two GaAsP sensors and an LI-190 on 2 summer days and 2 winter days under clear and cloudy conditions. The GaAsP sensors incorporate all the features of the recommended basic design, with one sensor type containing a G2711-01 (Type 2 sensor) and the other a G1118 (Type 4) photodiode.

Strong relationships between the GaAsP and LI-190 sensors were obtained with adjusted r^2 values exceeding 0.999 (Table 2). The relationship between GaAsP and LI-190 sensors is linear and the slope is close to 1, with the poorest relationship occurring on the cloudy winter day for the GaAsP sensor containing the G2711-01 photodiode. This sensor also showed a departure from linearity during the clear winter day (Figure 6b), and is a result of a slight perturbation in the vinyl tape used to occlude the lower portion of the diffuser to achieve cosine correction. Although this anomaly did not affect the r^2 compared to the G1118 sensor, instantaneous radiation measurements during the day would be subject to error. This problem was eliminated for the G1118 sensor by replacing the tape with a machined recess to expose the correct amount of diffuser. There appears to be no detectable difference in the performance of the two photodiodes other than that caused by small manufacturing variations in each individual sensor.

TABLE 2 *Adjusted r^2 values for two GaAsP sensors regressed against an LI-190 on 2 clear and 2 cloudy days during August and December 1998. The two GaAsP sensors contain two different photodiodes, G2711-01 and G1118.*

		Adjusted r^2	
Date	Sky	G1118	G2711-01
August 7, 1998	Clear	0.99990	0.99992
August 17, 1998	Cloudy	0.99990	0.99996
December 20, 1998	Clear	0.99966	0.99967
December 21, 1998	Cloudy	0.99985	0.99897

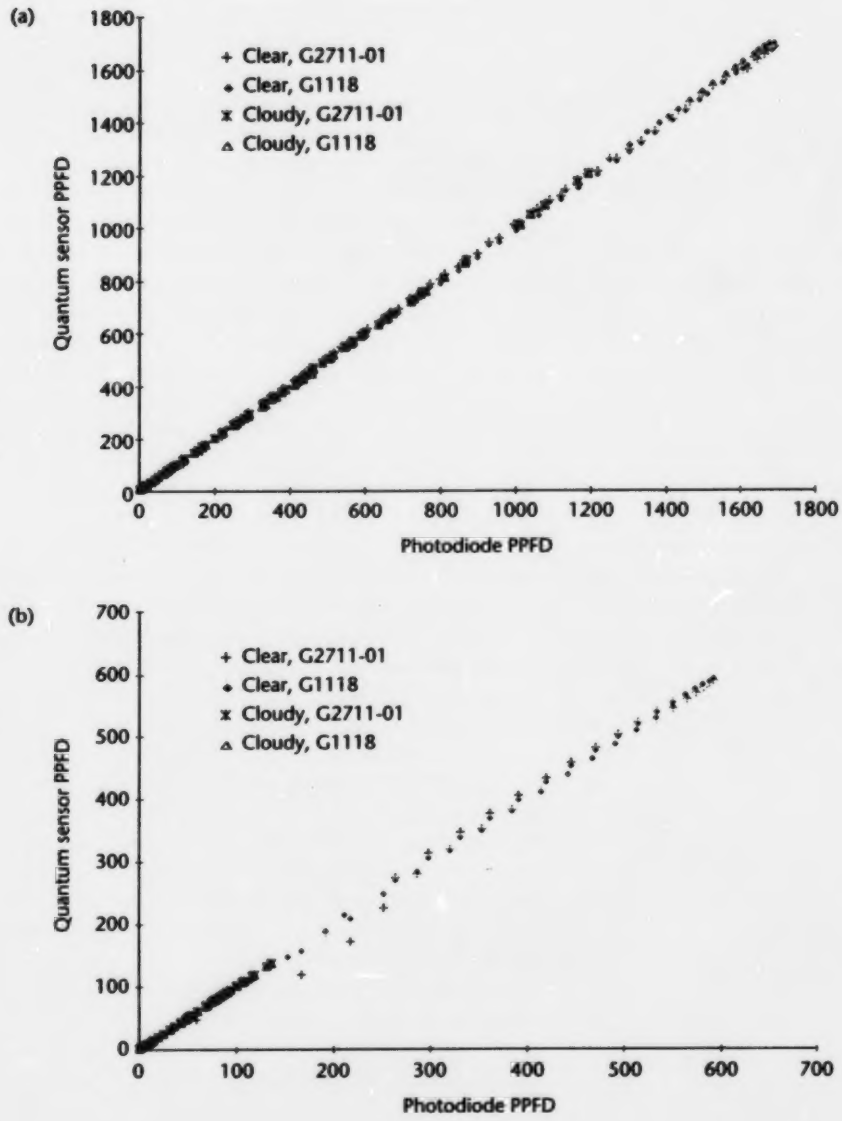

FIGURE 6 *PPFD obtained from two GaAsP sensors on 2 clear and 2 cloudy days compared with an adjacent LI-190 quantum sensor. The two GaAsP sensors contain different photodiodes, G2711-01 and G1118. (a) Clear day, August 7, 1998; cloudy day, August 17, 1998. (b) Clear day, December 20, 1998; cloudy day, December 21, 1998.*

Open-sky Testing with Standard Lamp Check

A selection of nine GaAsP sensors was placed on the roof of the Ministry of Forests office building in downtown Victoria. The GaAsP sensors, which included four slight variations on the basic design described above, were placed on a calibration plate with two LI-190 sensors. Data were collected continuously from June 1998 to June 2000 (see Calibration and Appendix 2). Data were not collected from September 21 to December 31, 1998, from April 5 to May 26, 1999, and from February 12 to March 17, 2000. Every 2–7 weeks, all the sensors were taken inside and calibrated using the LI-1800-02 standard lamp. An LI-190 sensor (Q15177, recalibrated by LI-COR in October 1998), stored in a dry camera bag when not in use, served as a control to provide a reference for the lamp output.

Over the period of calibration, four LI-190 sensors were actually used because two malfunctioned during October 1998 and were replaced. The replacements (Q15173 and Q15176) were sent to LI-COR for recalibration in November 1998. Calibration data from one of the LI-190 units (Q15173) was discarded because of a lack of stability throughout the year. Open-sky data for Q15176 were corrected for drift, based on standard lamp data measured over the same period. Data from the two calibrating LI-190 sensors (Q9594/Q15175 in 1998 and Q15173/Q15176 in 1999) were also compared to indicate the amount of variability from day to day that could not be attributed to the GaAsP sensors. Days on which the two calibrating LI-190 sensors showed deviation higher than 10% (8 days during January, October, and November 1999) were deleted from the data set. These events were caused by occlusion of one of the LI-190 sensors (i.e., by snow, ice, or bird-lime).

The design differences in the GaAsP sensors consisted of two variations for each of the two GaAsP photodiode packages: G2711-01 (Type 1, #41, 42 and Type 2, #71, 77) and G1118 (Type 3, #137, 146 and Type 4, #184–186). The design variations were in the size of the drill holes in the acrylic sensor body and the amount of machining of the cosine-correcting head. In Type 4 sensors (i.e., #184–186) (the design presented here) more machining was performed to arrive at a consistent diffuser height and to simplify final assembly.

Seasonal variation in daily open-sky calibrations (vs. LI-190) Figure 7 shows box plots of the daily calibration coefficients for the nine GaAsP and LI-190 sensors over 18 months under an open sky (see Glossary for explanation of box plots). Each daily calibration coefficient has been subtracted from, and divided by, the mean to yield the percentage deviation from a zero value for each sensor. Data show the distribution of the daily calibration coefficients during summer 1998 (June to September) (Figure 7a) and for summer, fall, and winter 1999 (January to November) (Figure 7b). Data for the period December 1999 to June 2000 are not shown because that part of the year was calibrated in 1999 and the pattern was similar in 2000. The data indicate that the photodiode (either G1118 or G2711-01) did not result in a consistent difference in sensor performance. Differences in data distributions for the four sensor types were consistent over the 2 years. However, consistent differences in data distribution also occurred within the same design Type (i.e., #184, 185, and 186).

The magnitude of the data spread doubled from 1998 to 1999. This increase was a result of more variable data from the late fall, winter, and spring months in 1999 when rainfall was more frequent and of longer duration, resulting in cosine error differences between test and calibration sensors. On

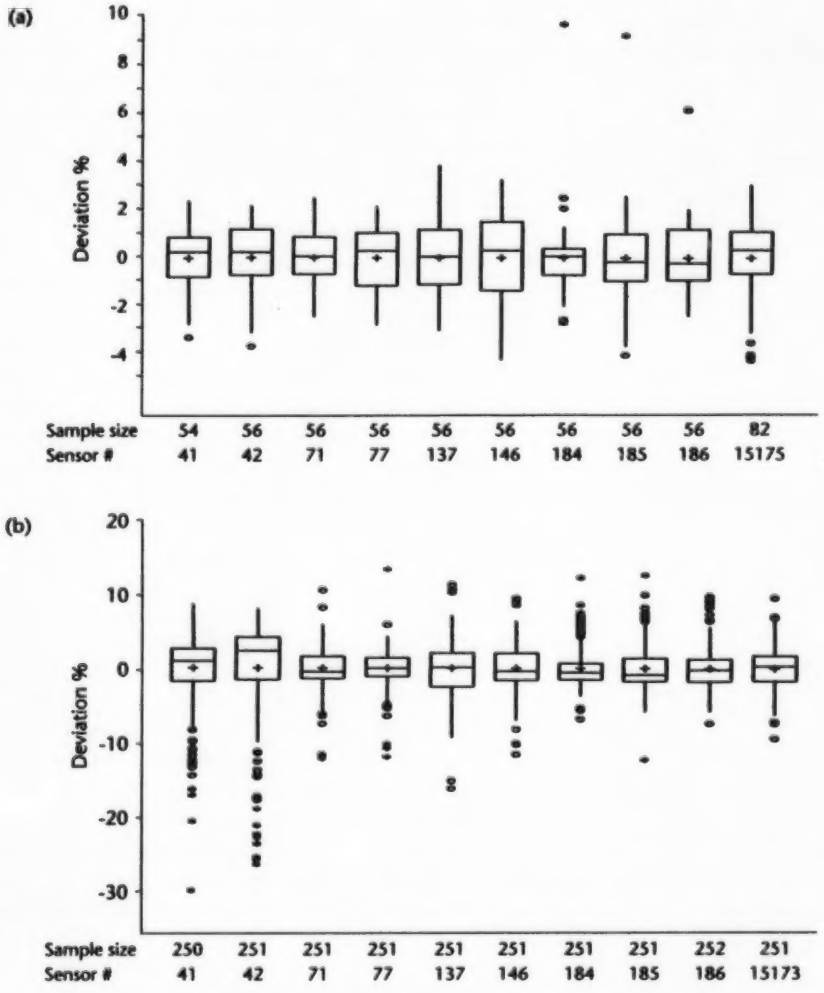

FIGURE 7 *Daily calibration coefficients of nine GaAsP sensors. GaAsP sensors include two different photodiodes and four construction "Types." Sensors with the G2711-01 photodiode include #41, #42 (Type 1), #71, and #77 (Type 2), and sensors with the G1118 include #137, #146 (Type 3), and #184–186 (Type 4). Plotted data are the percentage deviation of each daily calibration coefficient from the mean calibration coefficient for (a) June to September 1998 calibrated with LI-190 quantum sensors Q15175 and Q9594, and (b) January to November 1999 calibrated with Q15173 and Q15176 (only Q15176 was used for regressions). The two LI-190 sensors were calibrated against each other for each test period. Sample size = Number of data points (days).*

the whole, the day-to-day variability of the LI-190 sensors was of the same order of magnitude as that of the GaAsP sensors. A portion of this error was probably due to sensor drift.

Data shown in Figure 7a, which covers the greater part of the 1998 growing season, indicate that 50% of the daily calibration values for each sensor varied by less than 2% and most data were within 4%. One data point that varied by more than 5% on July 3, 1999 was an extreme outlier for #184, 185, and 186. During January to November 1999 (Figure 7b), 50% of the daily calibration values varied by 2–4% and most data were within 3–10%. For sensor Types 2–4, only a small percentage of data points fell within 5–15%; however, #41 and #42 (Type 1) showed deviations of up to 30%, with the data distribution skewed below the mean. We have no explanation for this deviation, except that this type of sensor (with the G2711-01 photodiode) may be susceptible to humidity and weathering that may result in an unstable signal. We observed a "spike" for #42 of about 23% during one of the lamp calibrations in February 2000 when the daily open-sky calibration coefficient was about 25% lower than the mean (Table 3). Lamp and open-sky calibrations for #42 both returned to normal after a several weeks in the office. This effect may be intermittent and not always picked up during lamp calibrations. Sensor #41 did not show the same effect (Table 3), but #41 and #42 were part of the first set (Type 1) of sensors produced and had had 2 full years in the field before this test. The Type 1 sensors may require photodiode replacement.

An increased signal due to a light-collecting effect was found to occur if the sensor head filled with water during heavy rain, particularly if a lens of water remained over the diffuser. Each sensor was provided with a drain hole that prevented lens formation, but some water remained around the diffuser until it evaporated. This is a sensor feature that could be improved to reduce errors during periods of rain.

Seasonal variation in standard lamp calibration of GaAsP and LI-190 sensors

Figures 8 and 9 show how the signal response of the nine GaAsP sensors and four LI-190 sensors changed from June 1998 to June 2000, as calibrated using the LI-1800-02 standard lamp. Both GaAsP and LI-190 quantum sensors exhibited signal drift over the 24-month test period. Except for #42, which exhibited a 23% increase in signal on February 12, 2000, the calibration drift of sensors containing the G2711-01 and G1118 packages was 0–6% over a single growing season (maximum period without recalibration in the field) and was 4–8% over the full 24 months. The general trend in signal is downward for

TABLE 3 *Standard lamp and open-sky calibrations for Type 1 GaAsP sensors and for the LI-190 calibration sensor on 5 days between October 1999 and June 2000*

Date	GaAsP sensor #41		GaAsP sensor #42		LI-190 sensor Q15176	
	Lamp[a]	Open sky[b]	Lamp[a]	Open sky[b]	Lamp[a]	Open sky[c]
26 Oct 99	46.9	216.1	50.2	195.6	6.2	1.04
25 Nov 99	46.9	214.6	49.7	201.1	6.3	0.93
12 Feb 00	47.8	211.8	63.1	150.8	6.2	1.03
18 Apr 00	45.9	232.6	49.7	216.6	6.4	1.11
02 Jun 00	45.9	216.5	49.2	196.21	6.3	1.06

a Standard lamp calibration constant (μA/1000 μmol·m^{-2}·s^{-1})
b Daily calibration coefficient from the slope of the regression curve versus Q15176
c Daily calibration coefficient from the slope of the regression curve versus Q15173

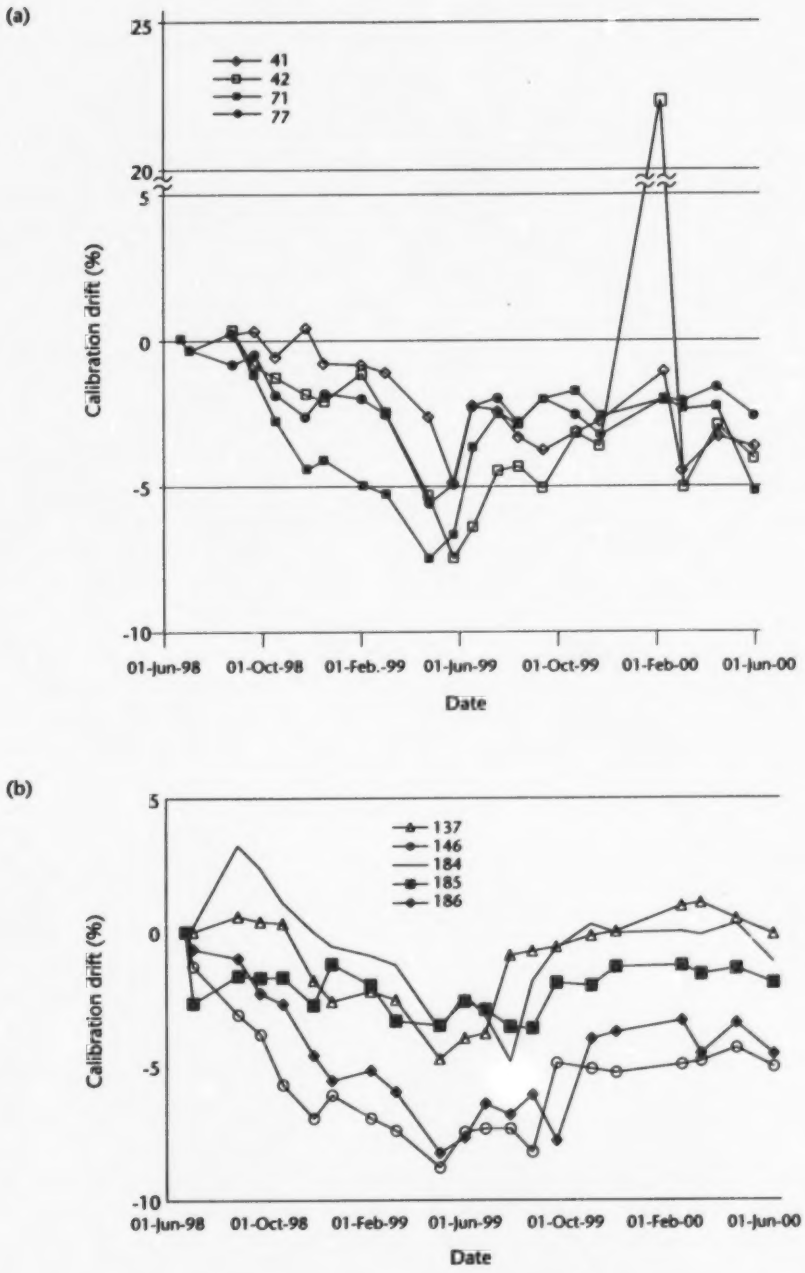

FIGURE 8 *Sensor drift of nine GaAsP sensors calibrated with the LI-1800-02 Optical Radiation Calibrator, June 1998 to June 2000. (a) Sensors (G2711-01), #41, #42 (Type 1), #71, and #77 (Type 2), (b) Sensors (G1118) #137, #146 (Type 3), and #184–186 (Type 4). See Figure 9 for LI-190 data.*

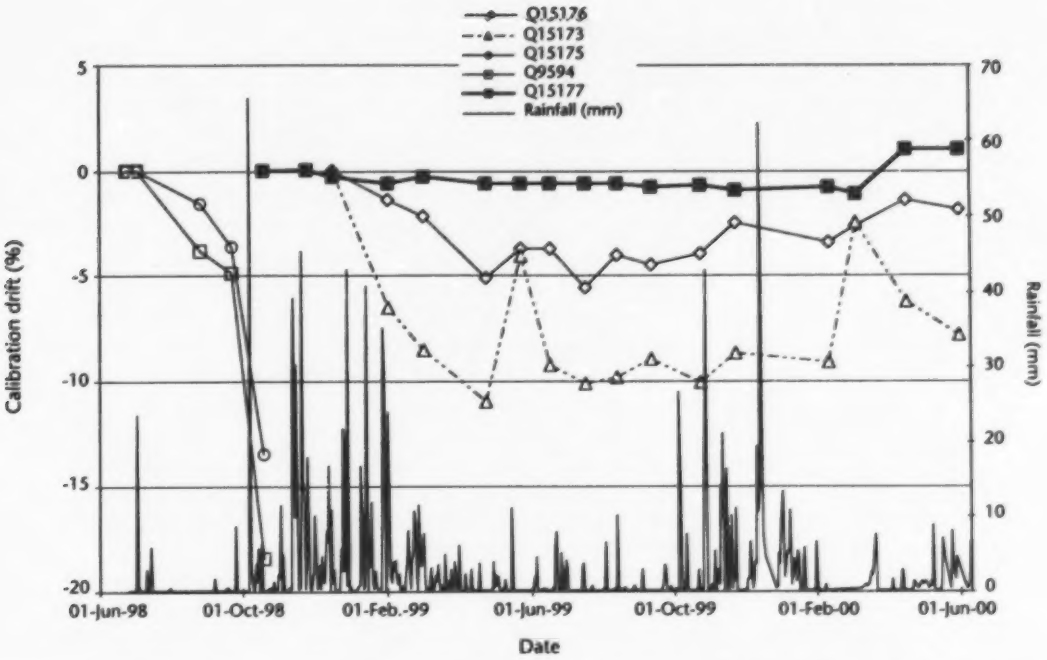

FIGURE 9 *Sensor drift of LI-190 quantum sensors calibrated with the LI-1800-02 Optical Radiation Calibrator. The calibrated lamp of the LI-1800-02 was replaced in May 1998 and March 2000. Q15173, Q15176, and Q15177 were returned to LI-COR for repair and recalibration in the fall of 1998. Q15177 was used as a check sensor and was kept dry and protected. Daily rainfall from June 25, 1998 to September 1999 was recorded at the Ministry of Environment weather station at Gonzales Hill, Victoria, B.C. Daily rainfall from September 1999 to December 1999 was collected at the calibration site using a tipping-bucket rain gauge.*

the first complete year (spring to spring), followed by a recovery. The reason for the gradual drift is not clear, but it could be due to diffuser weathering or to changes in the photodiode (the GaAsP sensor requires no filters, so filter deterioration can be ruled out). Weathering of the acrylic diffuser is a possibility, because the slow recovery of signal exhibited from May to November 1999 coincided with a change in cleaning procedure. From May 1999 onwards, readings were made before and after spraying and wiping using Electrosolve® contact cleaner, safe for plastics. This cleaning activity may have gradually removed a sun-damaged layer from the surface of the acrylic, but we have not tested this hypothesis. Another explanation for the drift of the GaAsP sensors is that newer sensors have not had a chance to "burn in." Pontailler (1990) mentions that newly made GaAsP (i.e.,Type 4) slowly reach relative stability, but does not indicate how long such a process takes. Hamamatsu Corp. provided no data on long-term stability or on how stability might be affected by weathering.

Figure 9 shows successive calibrations of the four LI-190 sensors with the LI-1800-02 standard lamp. Sensors Q9594 and Q15175, last calibrated by LI-COR 11 and 7 years previously, respectively, held their calibration within an average of 4% of the initial value during the summer months late-June to mid-September 1998. Signal attenuation, while at first gradual, increased sharply to more than 18% in the period from late September to mid-October 1998 after which the sensors were removed and returned to LI-COR for

recalibration. The two replacement sensors had been recalibrated by LI-COR a few weeks previously. A signal attenuation of 6–11% occurred in the replacement sensors over a 4-month period, after which they seemed to stabilize. Malfunctioning of the LI-1800-02 standard lamp can be ruled out by comparing it with the check sensor Q15177 (Figure 9). The check sensor shows a gradual 1% decline in signal over 17 months, with a correction of about 2% after installing a new calibrated lamp. The decline was most likely a consequence of a predictable change in lamp output with use.

Signal drift of the LI-190 sensors may have resulted from filter or diffuser weathering. The problem of filter weathering in sensors has also been mentioned by Pontailler (1990), but is apparently not general knowledge. The probable cause is moisture build-up inside the sensor body that degrades the filter array, resulting in a lower returned value and unstable readings (J. Wurm, LI-COR Inc., pers. comm., Oct. 1998). The sharpest drop in signal clearly coincides with the period of highest precipitation, beginning around the middle of September. Similar drift has been observed in sensors left for more than four seasons in the field in remote locations on Vancouver Island, indicating that poor maintenance is a factor. The extent of this problem for properly maintained sensors is by no means clear. The prudent strategy would involve frequent checks of field sensors with a newly calibrated quantum sensor and meter to be used only for this purpose and never exposed to moisture (Pearcy 1989). If deviations of more than 10% are observed, it would be wise to return the sensor for repair and recalibration.

Another potential problem with LI-COR calibrations was revealed as a consequence of being able to do calibration checks as soon as the sensor was removed from the moist environment. Some LI-190 units that exhibited calibration drift showed some self-correction after being stored in the office for several weeks (i.e., Q17173). A "spike" of recovery was observed for unit Q15173 during May 1999 and March 2000 (Figure 9). These recovery spikes coincided with the periods when all sensors were kept in the office for about a month. The signal had returned to its original low level after another month in the open. This raises the possibility of recalibrated units (those sent back to LI-COR) malfunctioning again soon after being installed in moist field conditions. These problems may be reduced by keeping the connector end inside a dry container (i.e., with the CR10 and desiccant pack) and by sealing around the lead port and base with silicon sealant at the time of field installation.

Comparison of open-sky and standard lamp calibrations Calibrations against LI-190 sensors under open-sky solar radiation always yielded a calibration coefficient 3–10% lower than standard lamp calibrations, presumably caused by the difference in spectral responses of the GaAsP photodiode, cosine errors, and transmission and reflection characteristics of the GaAsP sensor diffuser. The variability in the calibration coefficient offset was greatest between different sensor types, but the same types tended to have a similar offset. With a standardized design, an offset coefficient might be obtained by subtraction from the standard lamp calibration coefficient to obtain an estimate of the open-sky calibration coefficient. Acceptance of such a modest error may be preferable when considering the error associated with changes in the calibration sensor (LI-190) during successive calibrations under solar radiation.

Installation in the field and sensor mounting Sensors should be mounted on a stable surface that can easily be adjusted to ensure that sensors are level (Figure 10). A rugged steel mounting post may be constructed for $35–40, including parts and labour (Appendix 1). Silicon sealant can be used to attach sensors to the top plate (the sensors are easily removed with a utility knife). After allowing the sealant to set, sensors are levelled by adjusting the levelling screws. Finally, the securing bolts prevent any further movement.

The datalogger should be installed in a way that minimizes lead length to each sensor. We used 22-gauge, multi-stranded, single pair, shielded communications cable (Belden #8451) to connect sensors to the datalogger. The mating plug for the sensor lead plug must be soldered to the end of the lead (paying attention to polarity). This cannot be done beforehand because lead lengths will depend on the topography of the forest floor. Cable should be buried in a very shallow trench or hidden beneath sticks and logs.

Comparison of LI-190 and GaAsP sensors beneath a canopy A field test was conducted in 1998 at Spey Creek near Prince George, B.C., using 10 paired LI-190 and GaAsP sensor arrays placed in a birch stand of different plot densities of 0, 600, 1200, and 5300 (uncut) stems per hectare (st/ha). Three pairs of sensors were assigned to plots with a birch canopy (i.e., 600 st/ha, 1200 st/ha, and uncut). One pair of sensors was installed in a plot from which all birch had been removed. Each LI-190 and GaAsP sensor was attached side-by-side on top of a 1-m post. Hourly average PPFD was recorded between July 25 and November 12, 1998 to sample the period between full canopy and leaf fall.

FIGURE 10 *GaAsP sensor mounted on a steel post with levelling fixture.*

Table 4 shows that four LI-190s previously calibrated by LI-COR in April 1998 had significant problems. Q8493, Q8495, Q5764, and Q6614 drifted by 6.6%, 9.9%, 22.1%, and 28.9%, respectively. Pre- and post-season standard lamp calibrations in Table 4 show that only 10% of the GaAsP sensors drifted by more than 5% (#70) compared to 40% of the LI-190 sensors. In a previous field season (Table 5), the same GaAsP sensors demonstrated similar stability when pre-season roof-top calibrations (fall 1996) and post-season (May 1998) open-sky calibration coefficients were compared.

When drift for sensor pairs was accounted for in total drift, only three LI-190/GaAsP sensor pairs exhibit more than 5% drift: Q8495/#86, Q5764/#69, and Q6614/#74 (Table 4). The data in Table 4 are LI-1800-02 standard lamp calibrations, and the drift is calculated as a percentage change in calibration value from spring to fall 1998; from deployment in the field, to return to the office. The combined signal drift of the three sensor pairs is confirmed by a corresponding drift in the pre-season (roof of office) and whole field season (birch canopy) side-by-side LI-190/GaAsP solar radiation daily calibration coefficients in Table 6. This confirmation eliminates the possibility that the wrong calibration coefficient was applied to these LI-190 sensors. The LI-190 sensors were apparently mainly responsible for the malfunctioning of these sensor pairs.

TABLE 4 *Calibration data from the LI-1800-02 Optical Radiation Calibrator for paired LI-190 and GaAsP sensors in a birch stand at Spey Creek near Prince George, B.C. Pre–growing season and post–growing season calibration constants are presented with the percentage drift. Sensor pairs in which total drift changed by >5% are indicated in the table with bold type.*

Plot#	Density (st/ha)	LI-190 sensor calibration constant (μA/1000 μmol·m^{-2}·s^{-1})				GaAsP sensor calibration constant (μA/1000 μmol·m^{-2}·s^{-1})				Total drift (%)
		Sensor	Apr. 98	Nov. 98	Drift(%)	Sensor	Mar. 98	Nov. 98	Drift (%)	
10	0	Q5389	7.37	7.34	-0.45	67	11.75	11.87	1.00	-1.45
4	600	Q21374	5.30	5.26	-0.79	111	15.70	15.09	-4.06	3.26
4	600	Q8493	7.02	6.56	-6.51	70	18.75	17.27	-8.58	2.07
4	**600**	**Q8495**	**7.34**	**6.62**	**-9.86**	**86**	**20.77**	**20.43**	**-1.66**	**-8.20**
8	1200	Q21370	5.15	5.09	-1.15	66	12.14	11.86	-2.34	1.20
8	1200	Q21371	5.61	5.58	-0.57	68	12.05	11.86	-1.60	1.03
8	1200	Q21372	5.66	5.53	-2.37	81	19.91	19.70	-1.05	-1.32
9	**untreated**	**Q5764**	**6.64**	**5.17**	**-22.11**	**69**	**11.96**	**11.81**	**-1.21**	**-20.90**
9	**untreated**	**Q6614**	**6.54**	**4.65**	**-28.88**	**74**	**18.61**	**18.15**	**-2.56**	**-26.33**
9	untreated	Q8448	6.45	6.29	-2.47	80	20.63	20.35	-1.36	-1.10

TABLE 5 *Calibration drift of open-sky calibration coefficients after field season 1997/98*

GaAsP sensor #	Open-sky calibration (roof-top)		
	Sept. 1996	May 1998	Drift (%)
67	183.17	182.3	-0.50
111	no data	142.9	na
70	118.54	113.4	-4.57
86	98.02	99.1	1.12
66	180.78	175.6	-2.93
68	170.85	176.2	3.02
81	103.36	105.9	2.42
69	181.94	179.3	-1.44
74	111.35	113.2	1.62
80	101.71	103.2	1.43

TABLE 6 *Calibration data for the paired LI-190 and GaAsP sensors in a birch stand at Spey Creek near Prince George, B.C., July 25 to November 12, 1998. Shown are the calibration coefficients derived from the pre–growing season open-sky and the whole-season calibrations beneath the birch canopy. Calibration coefficients with >5% drift are indicated in the table with bold type. Regression statistics for the beneath-canopy regressions include the adjusted r^2, the dependent mean (the average of the season's hourly averages), and number of observations (hourly averages).*

				Cal. coefficients from regressions					
	Density	Paired sensors		Open sky	Birch		Canopy regression statistics		
Plot #	of birch (st/ha)	LI-COR #	GaAsP #	(roof) May 98	canopy, all season	% drift	Adj. r^2	Dep. mean (PPFD)	No. of obs. (n)
10	0	Q5389	67	182.3	185.29	1.64	0.9991	388.00	1620
4	600	Q21374	111	142.9	146.44	2.41	0.996	162.00	1647
4	600	Q8493	70	113.4	116.42	2.63	0.9955	157.88	1647
4	**600**	**Q8495**	**86**	**99.1**	**85.97**	**-15.31**	**0.9949**	**164.06**	**1647**
8	1200	Q21370	66	175.6	177.05	0.80	0.9981	95.15	1473
8	1200	Q21371	68	176.2	179.74	1.98	0.9673	61.42	1473
8	1200	Q21372	81	105.9	104.38	-1.47	0.9983	88.43	1473
9	**Untreated**	**Q5764**	**69**	**179.3**	**145.03**	**-23.66**	**0.9974**	**60.32**	**1685**
9	**Untreated**	**Q6614**	**74**	**113.2**	**98.4**	**-15.03**	**0.993**	**46.71**	**1685**
9	Untreated	Q8448	80	103.2	96.04	-7.44	0.9892	35.46	1684

The spectral response error beneath the birch canopy appears small compared with errors caused by sensor drift. For a tropical canopy, Pearcy (1989) calculated that if a GaAsP sensor pair was calibrated against a quantum sensor in open sky, then the GaAsP photodiode would read 3.2% higher than a quantum sensor. The spectral response error for the birch canopy may be determined by comparing the whole-season values to the pre-season calibration coefficients in Table 6. An error similar to the tropical canopy would be revealed by a negative drift value in Table 6, because sensor signal is inversely proportional to the calibration constant. For sensor pairs in the open (Q5389/#67), 600 st/ha (Q21374/#111, Q8493/#70), and 1200 st/ha (Q21370/#66, Q21371/#68, Q21372/#81), the drift in daily calibration coefficients was positive and at most 3.26%. Most of this error is also accounted for by total sensor drift determined by standard lamp calibrations. Drift for daily solar calibration coefficients for the sensor pair Q5389/#67 in the plot with no birch was 1.64%. Standard lamp calibrations in Table 4 show that the total drift of this sensor pair was -1.45%, resulting in a total deviation of 3.09%. Of the sensor pairs that did not malfunction, only sensor pair Q8448/#80 in the untreated plot had a negative drift (Table 6) that was not totally accounted for by total drift of the sensor pair from the standard lamp calibration in Table 4. After allowing for the lamp calibration (total drift of the sensor pair), this sensor pair showed a 6.34% ([-7.44]-[- 1.10]) decline in the calibration coefficient. This result allows for a spectral response error of approximately 3.2%, similar to that found by Pearcy (1989). The remaining 3.14% is not a large error for a sensor in very low light conditions. For example, 3.14% of the dependant mean for light level in the regression (35 $\mu mol \cdot m^{-2} \cdot s^{-1}$) is only 1.1 $\mu mol \cdot m^{-2} \cdot s^{-1}$. These light levels are approaching the limits of sensitivity of the instrument.

These data show that a spectral response error can be expected, at least in the most heavily shaded environments, but that the error is probably no

greater than a few percentage points and is probably acceptable when compared with other measurement and sensor drift errors. Pearcy (1989) also considered this error to be acceptable when considered with the reduced cost for a large number of sensors.

Box plots in Figure 11 show the distribution of the daily calibration coefficients for the whole season. The magnitude of drift in the three sensor pairs exhibiting the greatest change (Table 6) was not reflected in the daily variation, indicating that the change most likely took place as soon as the sensors were deployed. The percentage deviation from the mean calibration coefficient is lowest in the open plot and is comparable to data presented for calibration tests under open-sky conditions. For all the treatments under a birch canopy, most data points were between 5 and 30%, with outliers as far as 54%, but half the data varied by only 1–10%. The data distribution is generally broader under the canopy than in the open, but was very variable within and between treatments. The greatest data spread occurred in the two most dense treatments, 1200 st/ha (#68) and 5300 st/ha (#80). The heterogeneity of the light environment beneath the canopy most likely contributed to the variability of these data. The outliers were most likely the result of rainfall events, but this could not be confirmed because of lack of rainfall data for the site. These data suggest that below-canopy calibration of sensors should be done over more than 1 full day.

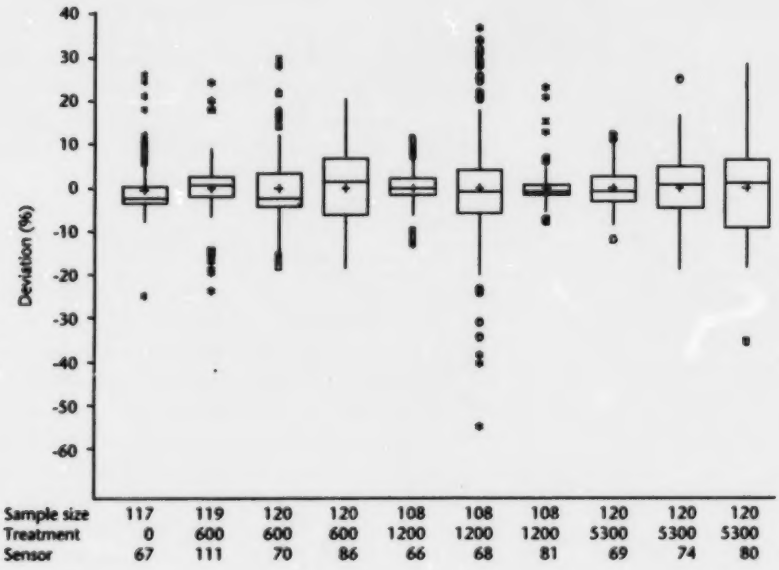

FIGURE 11 *Daily calibration coefficients for 10 LI-190 and GaAsP sensor pairs under a birch canopy of various densities of 0, 600, 1200, and 5300 (uncut) st/ha, July 25 to November 12, 1998. Plotted data are the percentage deviation of each daily calibration coefficient from the mean calibration coefficient for the measurement period. Sample size = Number of data points (days).*

Based on batches of more than 20 units, the GaAsP sensor can be manufactured for about $45, including parts and labour, which is a substantial saving over the cost of an "inexpensive" commercial sensor: about one-tenth the cost of an LI-190.

Material costs were $10–15 including the photodiode purchase (the G2711-01s were the least expensive). Labour charges for cutting and machining the aluminum, acrylic, and diffuser material was $8–10 per unit for more than 10 units. Assembly costs were $18–20, based on an estimate of 1 hour per unit.

Specifications for the GaAsP sensor include ruggedness, ease of installation and removal in the field, good levelling surface, good cosine correction, 300–660 nm spectral range (peak 640 nm), 400–660 nm with diffuser, 1 µs rise time, and an operating temperature of -10 to +60°C.

Nine GaAsP sensors were operated continuously under an open sky for 24 months. Standard lamp calibrations were performed every 4–7 weeks and continuous full-day solar calibrations were conducted with at least one LI-190 as a calibration standard. Standard lamp calibrations for eight of the sensors showed a drift of <6% per growing season and 3–8% over the whole 24 months. However, one Type 1 sensor (#42) returned a signal 23% higher than expected in February 2000. Most daily calibration coefficients derived from solar calibrations, for all nine sensors, varied by 2–4% (half of the values varied by <2%) from June to September 1998, and by 3–10% (half the values varied by <4%) from January to November 1999. A skewed negative data distribution indicated an intermittent stability problem for Type 1 sensors #41 and #42. A portion of this variation may have been caused by rainfall events. Blocked or partially blocked drainage holes can cause a large measurement error resulting in a low calibration coefficient. However, the "spike" in the standard lamp calibration for #42 suggests that the G2711-01 photodiode may be malfuntioning in the Type 1 sensors. Testing and perhaps replacement of the photodiode after 3 years of continuous operation would be prudent. Subsequent versions of the sensor (Types 3 and 4) with the G1118 resin-coated photodiode may be more robust.

LI-COR's specifications indicate a drift of <2% per year for the LI-190 quantum sensor. A LI-190 check sensor, that was always stored in a camera bag when not in use, remained well within specifications over a 24-month period. However, four LI-190 sensors, two of which were recently calibrated, drifted 5%–18.5% during continuous open-sky testing. Similar drift was observed during field testing under a birch canopy for GaAsP and LI-190 sensors over one summer and fall. The GaAsP sensor, although not perfect, did compare favourably with the instrument we were using as our standard. The drift problems may be inherent in photodiode technology rather than in the insufficiency of any particular sensor design. However, more testing would be necessary to precisely determine the causes of drift.

Under a birch canopy, variation of daily calibration coefficients was 5–55%, but 50% of the calibration coefficients over all treatments were within 10% of the mean. Variability of daily calibration coefficients in certain treatments suggests the need for care in making *in situ* calibrations for 1 full day or less. Using an open-sky calibration (GaAsP sensors against quantum sensor) would possibly result in a maximum error of about 7% in the most shaded environments—a relatively small error in a low-light environment.

If possible, newly constructed sensors should be placed outside for a short period before installation. This "burns them in" and allows identification of non-functional sensors. Diffusers of sensors deployed beneath the canopy should be cleaned as often as possible; an ideal frequency would be once a week, but frequency will depend upon site location and canopy type. Calibrations should be done at least twice a year, pre- and post-measurement season. Unless light measurements are required for the whole season, we recommend removing sensors from the field during the winter in very moist environments. These recommendations also apply to proprietary sensors.

We conclude that construction of GaAsP sensors would be desirable for studies in which large numbers of sensors are required; that is, more than 20. Otherwise the time and expense involved in construction, testing, and calibration outweigh the savings.

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GLOSSARY

Box Plots describe several of a data set's main features. These features include spread, centre, degree of departure from symmetry, and identification of outliers. To construct the box plot, the samples are ordered from smallest to largest to determine the sample median. The bottom and top edges of the box are located at the sample 25th and 75th percentile. The 25th percentile is median of all samples less than the sample median and the 75th percentile is the median of samples greater than the sample median. If the number of samples is odd, then the sample median is included in the determination of both 25th and 75th percentiles. The distance between edges of the box is called the interquartile range (IQR). The centre horizontal line is drawn at the sample median and the "+" sign is at the sample mean. The central vertical lines (whiskers) extend from the box as far as the data extend, or if data extend further, the whiskers end at a distance of 1.5 IQR. Data points occurring less than 3 but more than 1.5 IQRs from the box are marked with a "o" and those more than 3 IQRs are marked with an "*". For further information, consult Tukey (1977).

Cosine Correction and Lambert's Cosine Law—A sensor that conforms to Lambert's cosine law with respect to its angular response to light is said to be cosine-corrected. Lambert's cosine law states that the irradiance falling on a flat surface varies as the cosine of the incident angle. Thus the angle of incidence to a flat surface of a beam of radiation of a given cross-sectional area is inversely proportional to the area of spread and directly proportional to the irradiance (after Biggs 1986).

Ideal Photon Response—A sensor exhibiting an ideal photon response responds equally to all photons in the 400–700 nm waveband and is cosine-correct (Biggs 1986).

A **Photodiode**, also called a photocell or photovoltaic cell, is the light-sensitive component of a photoelectric sensor. The general principle of operation is similar for all photodiodes (Hamamatsu Corp. 1995). A P-layer at the active surface and an N-layer as the substrate form a PN junction that operates as a photoelectric converter. The neutral region between the P- and N-layers is called the depletion layer. Spectral and frequency response and response time are controlled by varying the characteristics of these layers (i.e., thickness). When light strikes a photodiode, the photovoltaic effect can occur only if the light energy exceeds the band gap energy (Eg), which is essentially the energy required to excite an electron so that it can migrate toward the N layer (cathode). Eg then determines the limiting wavelength, which, for GaAsP at room temperature, is 1.8 eV or a wavelength of 700 nm. The cut-off wavelength is determined by the material used in the layers and by the spectral transmittance of the window material.

Photosynthetic Photon Flux Density (PPFD) is defined as the photon flux density of PAR. PPFD is the number of photons in the 400–700 nm waveband incident per unit time on a unit surface, and is usually expressed in micromoles per square metre per second ($\mu mol \cdot m^{-2} \cdot s^{-1}$) (Biggs 1986).

Photosynthetically Active Radiation (PAR) is defined as radiation in the 400–700 nm waveband. PAR is the general radiation term that covers both its measurement in terms of photons and the radiant energy in watts (Biggs 1986).

Planar Diffusion Type GaAsP Photodiode—The planar diffusion type is one of two types of GaAsP photodiode manufactured by Hamamatsu Corporation. The planar diffusion type is characterized by a low-level dark current and a spectral response of 300–660 nm. Dark current is produced while no light is striking the active surface. The Schottky type has a slower rise time and a high UV sensitivity, and requires some filtering for use as a PAR sensor.

Assembly of the GaAsP Sensor

The light sensor is made up of several parts: an outer aluminum sleeve, an acrylic body, a diffuser, the photodiode, and a lead terminating in a two-pin plug (Figure 2).

Photodiode The recommended photodiode is the GaAsP G1118 or G2711-01 manufactured by Hamamatsu Corporation (Figure 2). The G1118 is round (cut flat on two sides), 5.93 mm in diameter, with two long pins arising from the back. The negative pin is marked with a tiny hole in the resin package. The G2711-01 is rectangular, 5.98 by 6.61 mm (6.75 mm diagonally) with two common negative pins diagonally opposite each other and a single positive pin (the fourth is non-functional).

Preparation of sensor housing

1. The sensor body is made up of a piece of aluminium tubing (22.23-mm [⅞″] outer diameter, 19.06-mm [¾″] inside diameter) pared to 25-mm sections on a lathe, and a 21-mm long piece of clear or black 19.06-mm (¾″) cast acrylic round stock cut precisely square. The extruded round stock is less expensive, but it is not perfectly round and it is difficult to machine.
2. As shown in Figure 2 the acrylic body is drilled through the centre to accept the photodiode. The G1118 requires a "letter A" drill (5.953 mm) and for the G2711-01 a 7.144-mm (9⁄32″) drill bit will suffice. A second 15.875-mm (⅝″) cavity is made to within 5 mm of the top of the sensor to hold the lead wires and photodiode pins.
3. A recess, machined according to the drawing (Figure 3), facilitates positioning the diffuser and allows only the required amount of diffuser to be exposed.
4. Cutting away the material adjacent to the diffuser minimizes light reflection and facilitates shedding of water.
5. Diffusers can be cut to a diameter of 7.85 mm using a laser or XY plotter/router from translucent "sign white", 3.35–3.39-mm (⅛″) cast acrylic sheet (Acrylite GP 015-2, Cyro Canada, Inc., Mississauga, Ont.).

Making sensor leads

6. The external lead and plug is made from a 16-gauge trailer plug (a smaller gauge would suffice) and a 40-cm piece of unshielded, 22-gauge, single-pair, multi-stranded communications wire (Belden #9222). Solder the trailer plug to the communications wire, ensuring that the soldered connections are insulated and the connection sealed with heat-shrink tubing. Maintain the same wire colour and polarity for the lead plug; this avoids polarity problems during field installation. For consistency, wires should be attached so that the red (+) lead terminates in the metal bayonet part of the plug.
7. Strip the insulation from the opposite end of the lead to reveal about 5 cm of wire and then about 5 cm of 3.175-mm (⅛″) shrink-wrap should be heat shrunk so that it overlaps the cut end of the grey plastic coating by a few millimetres. This will allow a tight fit for insertion into the lead port.

Sensor assembly

8. If clear acrylic is used, the top of the sensor will need to be painted with matte-black model paint (Testors or Humbrol), and this should be done before fitting the diffuser. Apply several coats and allow to dry well.
9. Bond the diffuser in place by pressing the diffuser into the recess. Use cotton gloves to avoid marking the diffuser, because any surface damage or roughness will affect optical properties and promote the build-up of dust and dirt. If the diffuser does not fit exactly, burrs may be taken off with fine wet and dry sandpaper. Flip the acrylic body over and apply a very small amount of the acrylic solvent (methylene chloride) to the edge where the bottom of the recess meets the bottom of the diffuser; add only enough to be drawn into the bonding surfaces. Any surplus may mark the surface of the diffuser and interfere with the proper seating of the photodiode. When buying the bonding agent, be sure to purchase the applicator bottle with the hypodermic-like applicator. **Work in a well-ventilated area and wear eye protection.**
10. Prepare the photodiode for placement inside the acrylic body.
    G1118: Hold the photodiode in a small vise (gently) and use a wire wrap tool to attach positive and negative leads of solid 30-gauge wire (about 10 cm) to the respective terminals of the photodiode. The wrapped joint can be secured with a drop of solder to give a secure connection. The joint should be no nearer than 5 mm from the package and soldering time should not exceed 5 seconds at 260°C using a temperature-controlled soldering iron. The exposed leads should be insulated with a small-diameter heat-shrink tubing.
    G2711-01: The side with both positive and negative pins is on the same side as the connection to the active area (visible as a very fine silver wire going to the positive pins). Wire-wrapping is not possible with this photodiode because the pins are much shorter. The solder joint should be no nearer than 1 mm from the package and soldering time should not exceed 3 seconds at 230°C using a temperature-controlled soldering iron. The pins must be bent back to allow the package to fit into the access hole. One-eighth-inch heat-shrink tubing may be used to prevent the soldered pins from shorting.
11. The photodiode may be fixed permanently in place against the underside of the diffuser with clear epoxy resin. However, it is preferable not to have any bonding agent between the photodiode window and the underside of the diffuser because degradation and yellowing may occur over time. Be sure that the photodiode is lying flat against the underside of the diffuser. Clear epoxy resin will secure the photodiode flush against the underside of the diffuser, but will preclude re-using the sensor if the photodiode fails. Otherwise the photodiode may be held in place with a small amount of non-corrosive silicon sealant, allowing removal and replacement if necessary.
12. The acrylic sensor body may be glued inside the aluminium tube with epoxy resin. If the epoxy-covered sensor body is inserted bottom first and then inverted on a flat hard surface, the diffuser will be flush with the aluminum edge when dry.
13. Now the lead port may be drilled. Lead access is through a 3.572-mm (9⁄64″) hole drilled through the side of the sensor 8.5 mm from the base to the centre of the drill hole.

14. Using a jig or support to steady the drill bit, a drain hole of about 2.5 mm diameter may be drilled through the rim at about 45 degrees to the surface of the acrylic photodiode housing. This hole allows water to drain from the sensor head.
15. The lead end should be pushed through the lead port (with some twisting) in the side of the sensor so that about 0.5 cm is visible on the inside. Tightly crimp a small cable-tie around the lead where it appears inside the sensor body and seal with non-corrosive silicon sealant. A non-corrosive sealant/adhesive should be used to avoid problems due to out-gassing of corrosive acids.
16. Solder the leads (paying attention to polarity), insulate them, and push them down inside the cavity. The open base may then be filled with sealant (paying attention to also seal around the inside of the lead port) and allowed to harden.
17. The sensor is ready for testing after touching up the black paint on the sensor head and rim.
18. Finally, an identification label (i.e., a serial number) should be affixed to the sensor. We used the KROY DuraType 240 with the industrial black lettering on a silver background.

Assembly of Cosine-Correction Testing Apparatus

1. Construct a box of ⅝" ranger board, with one side large enough to accept a light source.
2. Drill through the side of the box to allow a piece of 19.06-mm (¾") acrylic round stock to be inserted.
3. Fit a dial to the round stock protruding outside the box. Attach a cradle to the inside to accept the test sensor. The cradle must enable the test sensor to be rotated in the path of the light beam about an axis through the centre of the sensor.
4. Using a protractor, make a scale from 0 to 90 degrees so that the dial can be set to each of the following zenith angles: 0, 10, 20, 30, 40, 50, 60, 65, 70, 75, 80, 82, 84, and 86 degrees.

Assembly of Sensor Supports for the Field

1. Required materials include two discs of 6.35-mm (¼") thick steel. One disc has three holes of 4.763-mm (3⁄16") diameter equally spaced around an imaginary circle of a 22.23-mm (⅞") radius. The second disc has the same three holes plus three more equally spaced on a 31.75-mm (1¼") circle. These last three holes are threaded for machine screws (e.g., 10 x 32).
2. The lower disc is welded to 25.4-mm (1") steel pipe about 1-m long with the free end threaded. Pipe may be cut into sections of about 1 m. The free end of the pipe is threaded with "pipe thread" that accepts off-the-shelf couplings. A union is used to couple the unit to another threaded section of pipe.
3. For assembly, sections of pipe must be joined to achieve the desired height. The upper and lower discs may be attached securely using three machine bolts (31.75 mm (1¼") long) using the inner radius holes. The threaded holes hold 19.06-mm (¾") machine screws for levelling the upper disc on which the sensor may be secured with silicon sealant.

```
Program: To read one sensor connected to Channel 1 single ended
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:

*   1       Table 1 Programs
      01: 10        Sec. Execution Interval

    01: P1          Volt (SE)
      01: 1         Rep
      02: 3         25 mV slow Range
      03: 1         IN Chan
      04: 1         Loc :
      05: 1         Mult
      06: 0.0000    Offset

    03: P92         If time is
      01: 0         minutes (seconds—) into
      02: 10        minute or second interval
      03: 10        Set high Flag 0 (output)

    04: P77         Real Time
      01: 220       Day, Hour, Minute

    05: P71         Average
      01: 1         Reps
      02: 1         Loc
```

APPENDIX 3 Costs and sources

Material	Source	Cost ($Cdn.)
Acrylic rod (cast) ¾″	Industrial Plastics Ltd. 3944 Quadra Street Victoria, BC V8X 1J6 Tel: 250 727-3545	$21.33/m
Acrylite GP 015-2 (sign white) Acrylic sheet ⅛″ cast	Industrial Plastics Ltd. Manufactured by: Cyro Canada Inc., Mississauga, Ont.	$55/sq. m
Adhesive (clear sealant) Dow Corning (non-corrosive)	Queale Electronics 485 Burnside Road East Victoria, BC V8T 2X3 Tel: 250 388-6111	$27.00
Aluminum tubing ⅞″ (outside diameter), ⅛″ wall	Shamrock Metals Inc. Keating Industrial Park #3-6820 Veyaness Road Saanichton, BC V8M 2A8 Tel: 250 652-6577	$7.38/m
Cable, Belden 8451, 22 gauge, single pair, shielded, stranded	Queale Electronics	$0.66/m
Cable, Belden 9502-U, 22 gauge, single pair, unshielded, stranded	Queale Electronics	$0.49/m
CR10X Datalogger - Measurement and control module (basic model)	Campbell Scientific Corp. 11564 149 Street Edmonton, Alberta T5M 1M7 Tel: 780 454-2505	$1950
Epoxy resin, clear (good quality)	Queale Electronics or a hobby store	$7.00
GaAsP photodiodes G1118 and G2711-01	Hamamatsu Corporation 360 Foothill Road Box 6910 Bridgewater, NJ 08807-0910 Tel: 908 231-0960	G1118: 1–9 @ $24.00 each 10–49 @ $13.00 each G2711–01: 1–99 approx. $6.00 each
Heat-shrink tubing assorted, 1/16″, ⅛″, 3/16″, and ¼″	Queale Electronics	$1.65–$3.30/m
Labeller K244SE or KROY DuraType 240 (KLS industrial tapes)	Graphics Products, Inc. PO Box 4030 Beaverton, OR 97076-4030 Tel: 503 644-5572	$485 (tapes $30)
LI-1800-02, Optical Radiation Calibrator	LI-COR Inc. 4308 Progessive Avenue Lincoln, NE 68504 Tel: 800 645-4267 or 402 467-0700	$5000

Material	Source	Cost ($Cdn)
LI-190SA, Quantum Sensor	LI-COR Inc.	$500
Methylene chloride (solvent) 55 ml	Industrial Plastics Ltd.	$3.39
Paint, matte-black (Testors, Humbrol)	Hobby shop	$5.00
Resistors, ¼ watt, 1% (432 ohm)	Queale Electronics	$4.00/100
Soldering station, Weller	Queale Electronics	$139.95
Trailer connector, 2 pin	Queale Electronics	$3.00 each
Wire wrap, 30 gauge	Queale Electronics	$0.44/m
Wire wrap tool	Queale Electronics	$11.99